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Applications of Informatics and Cybernetics in Compact Solar Combisystem for Multifamily Residential Buildings

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Abstract: This paper focuses on the optimization of a new solar thermal system and the analysis of a demonstration project. The solar thermal system has been developed by three industrial partners working in cooperation with Riga Technical University. The industrial partners joined their forces to develop a new product, which could benefit their core business. The basic product idea is a solar thermal system coupled with a wood pellet system. This is a 100% renewable energy solution for space heating and domestic hot water in multifamily buildings. The system is compact and factory assembled in a standard shipping container. However, potential for optimization both exists for increasing solar fraction and for reducing parasitic electricity demand. The first part of the paper describes the system concept and design, and the methodology proposed for the identification of an optimized set of operating parameters based on informatics, cybernetics and dynamic simulation. The second part of the paper shows a case study where the proposed optimization methodology is used for the optimization of a demonstration project implemented in Latvia.

Key words: Solar and pellet combisystem, optimization, operating parameters.

1. Introduction

In Nordic countries heat energy account for a significant share of household costs. In Latvia 70% of the total heat energy produced in the country was used for household purposes in 2010 [1]. The increase in price for fossil fuels has forced households to consider alternative heating systems.

If non fossil energy sources for heat production in Latvia are compared, then wood logs and wood chips for stoves and boilers today have the greatest share of the renewable energy market. At the same time, wood pellet fired boilers have also become popular [1].

Studies by Thur et al. [2] and Persson [3] have shown that primary energy savings can be achieved by introducing solar thermal technologies for heat supply. When combining solar thermal technologies and pellet boilers, a reduction of pellet consumption can thereby be achieved. Possibilities for the integration of pellet stoves and solar heating systems for single family house are discussed by Persson et al. [4]. Weiss [5] and the SOLARGE project report [6] present examples of solar combisystems integrated into multi-family buildings. The sizing of the solar combisystems, both for SH (space heating) and DHW (domestic hot water) preparation, at different loads has been studied by Lund [7]. Experimental research by Rochas [8] on the optimization of the two parameters—heat storage and pellet boiler constructive parameters—was also done. In addition to the primary energy savings gained by means of the solar combisystem, emissions from boilers can be significantly reduced. During summer months, limits can be placed on both the boiler’s working time and the number of start/stop routines. Both emissions and the thermal performance of the auxiliary heater should be taken into account to optimize the performance of the solar combisystem. Studies by Fiedler et al. [9] showed how to size and control commercially-available solar and pellet heating systems. Research on

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improving boiler controls and potential energy savings in heating systems is explained by Liao and Dexter [10]. Their results show that when boiler controls are improved it is possible to achieve energy savings of 20%.

In Latvia, compact solar combisystems are produced and entering the market. This compact system is factory assembled in a standards shipping container, where all main components are mounted (water accumulation tank, pellet boiler, pellet store and feeding system, DHW and SH loops, controller and all necessary valves and expansion vessels). This high degree of prefabrication reduces installation costs and possible plumbing errors compared to typical onsite installations. The container is transported close to the building and the installation just includes the connection to the SH and DHW systems of the building and the solar collectors. However, solar combisystems are complex systems and have interactions with extra subsystems. These interactions affect the overall performance of the solar part of the system and leave room to system optimization [5].

In this study, a methodology for optimization and improvement of performance of solar factory assembled compact combisystem is proposed. The aim of the methodology is the identification of an optimum set of OP (operating parameters), which can be used during system installation at a specific site/building. The methodology aims at reducing computational effort, while keeping acceptable confidence level of the results. The methodology is based on benchmarking analysis using the FSC (fractional solar consumption) concept [5]; system dynamic simulations using TRNSYS [11]; statistical modeling based on multi-correlation analysis; optimization of the multi correlation equation using the GRG2 (generalized reduced gradient) nonlinear optimization code [12]. The methodology has been tested on a demonstration project implemented in a multifamily residential building in Latvia.

The paper is organized as follows: Section 2 discusses the background information; Section 3 introduces the methodology; Section 4 presents case study; Section 5 gives conclusions.

2. Background Information

The paper deals with the optimization of a specific compact solar combisystem manufactured in Latvia. The main focus of the system is compactness: the pellet boiler (from 100 kW to 200 kW), the buffer tank, the pellet storage (8 tons) and all hydraulic components are installed in a standard size shipping container (length 6.0 m, width 2.9 m, height 3.0 m). This makes the system easy to transport and simple to install (typically less than one week onsite work). Additional buffer store can be added on site in function of the selected solar collector array. The system is assembled and tuned at the factory allowing higher quality standards and minimizing the risk of error during installation. The solar combisystem consists of:

(1) Heat suppliers—a pellet boiler and solar collectors;

(2) Heat storage—an accumulation tank (2.35 m^3);

(3) Heat consumers—SH and DHW loops (preparation and recirculation);

(4) A technical unit containing all necessary components for the system (pumps, expansion vessels, valves, HEX (heat exchangers), etc.).

The heat accumulation tank is designed with auxiliary volume of 0.55 m^3. Set temperature level for the auxiliary volume is maintained by the pellet boiler. However, the controller is set with a priority function for solar energy. Hot water from the accumulation tank is supplied to the HEX1 and HEX2 for SH and DHW(Fig. 1).

The defined temperature for SH and DHW preparation is controlled by three-way valves M1 and M2. The set point temperature for DHW is 55 ℃. The supplied temperature for the SH system is regulated as a function of the outdoor temperature and a predefined heating curve. The return temperature from the SH and DHW (> 35 ℃) is sent to the middle of the accumulation tank.

The three-way switching valve M3 directs the return DHW flow to the bottom of the tank if flow temperature is below the selected set point. This technical solution maintains low temperature in the bottom of the tank.

The container where this compact solar combisystem is assembled includes a pellet store unit, which is made by three silos with pneumatic supply system to the boiler stand-by storage (50 kg capacity). Pellets are then fed to the burner by a screw-type conveyor. The vertical walls of the container correspond with the boundary walls of the pellet storage. The total capacity of the pellet store unit is up to 8 tons of pellets.

3. Methodology

The methodology proposed is based on benchmarking, dynamic simulations and multi-correlation analysis. The aim of the optimization is to maximize the solar income of a compact solar combisystem manufactured in Latvia. The solar income is calculated as Eq. (1):

$$\mathrm{MAX}\left\{ \mathrm{I} = \mathrm{Q}_{solar}\,[\mathrm{MWh}]\cdot \mathrm{AEt}\left[\frac{\mathrm{US\$}}{\mathrm{MWh}}\right] - \mathrm{W}_{par}[\mathrm{kWh}]\cdot \mathrm{EEt}\left[\frac{\mathrm{US\$}}{\mathrm{kWh}}\right]\right\} \quad (1)$$

Where I represents the solar income from solar energy, Q_{solar} is the useful solar energy gain, AEt is the auxiliary energy tariff, W_{par} is the parasitic electricity consumption, EEt is the electricity tariff.

Useful energy gains and parasitic electricity consumption can be expressed as function of the following operating parameters (Eq. (2)):

$$\begin{cases} Q_{solar} = f\left(\dot{m}_{c,hex3,h}, \dot{m}_{c,hex3,c}, \Delta T_{c,ON}, \Delta T_{c,OFF}, T_{Set,M3}\right) \\ W_{par} = g\left(\dot{m}_{c,hex3,h}, \dot{m}_{c,hex3,c}, \Delta T_{c,ON}, \Delta T_{c,OFF}, T_{Set,M3}\right) \end{cases} \quad (2)$$

Where $\dot{m}_{c,hex3,h}$ represents the flow rate, solar collector loop, hot side of heat exchange HEX3 (Fig. 1), $\dot{m}_{c,hex3,c}$ is the flow rate, solar collector loop, cold side of heat exchange HEX3 (Fig. 1), $\Delta T_{c,ON}$ is the upper dead band temperature, solar differential controller, $\Delta T_{c,OFF}$ is the lower dead band temperature, solar differential controller, $T_{Set,M3}$ is the set temperature, switching value M3(Fig.1).

For dynamic simulation TRNSYS, which is a software environment is used to simulate the behavior

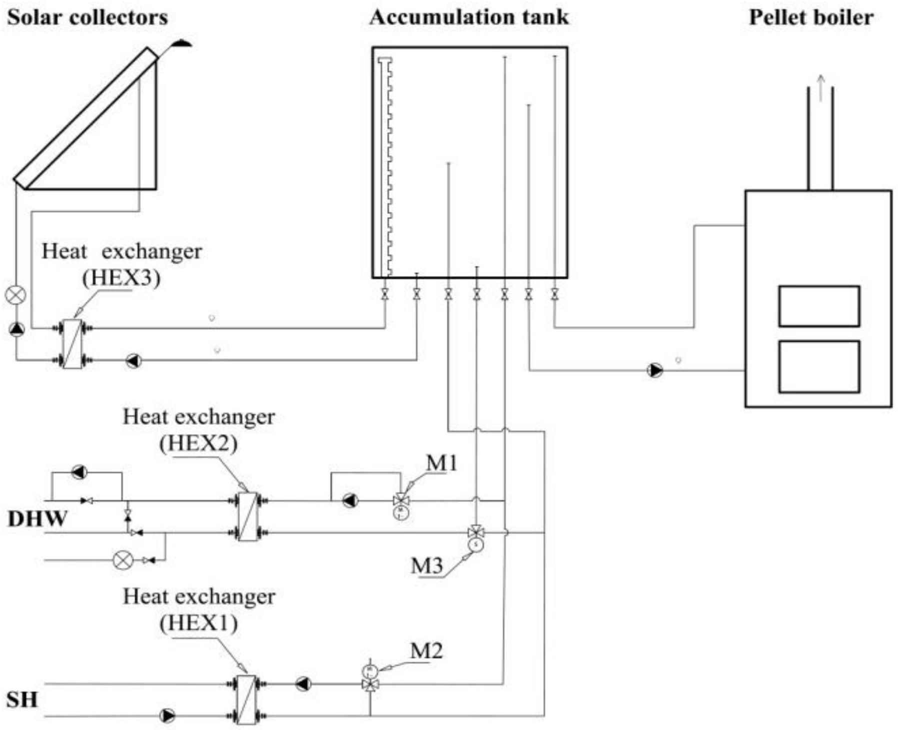

Fig. 1 Simplified hydraulic scheme for the solar combisystem.

of transient systems. In this software a detailed deterministic mathematical model of the solar combisystem has been developed and validated.

The proposed methodology for optimization consists of the following steps:

Setting of targets using benchmarking analysis and FSC concept include dynamic simulation with a first set of OP (default values given by manufacturers and installers);

(1) Dynamic simulation using random sampling of OP between feasible ranges;

(2) Multi-correlation analysis between the outputs from simulations and the random sampling of OP;

(3) Optimization of the multi-correlation equation using GRG2;

(4) Refining subroutine with reduced ranges around optimized values;

(5) Comparison to benchmarks values.

The algorithm of the proposed methodology is shown in Fig. 2.

Benchmarking analysis and fractional solar consumption: The selection of the collector area that can be installed using the described compact solar combisystem can be selected case by case depending from user requirement and financial possibilities. Benchmarking analysis is therefore needed to understand the technical potential for optimization at a selected collector area.

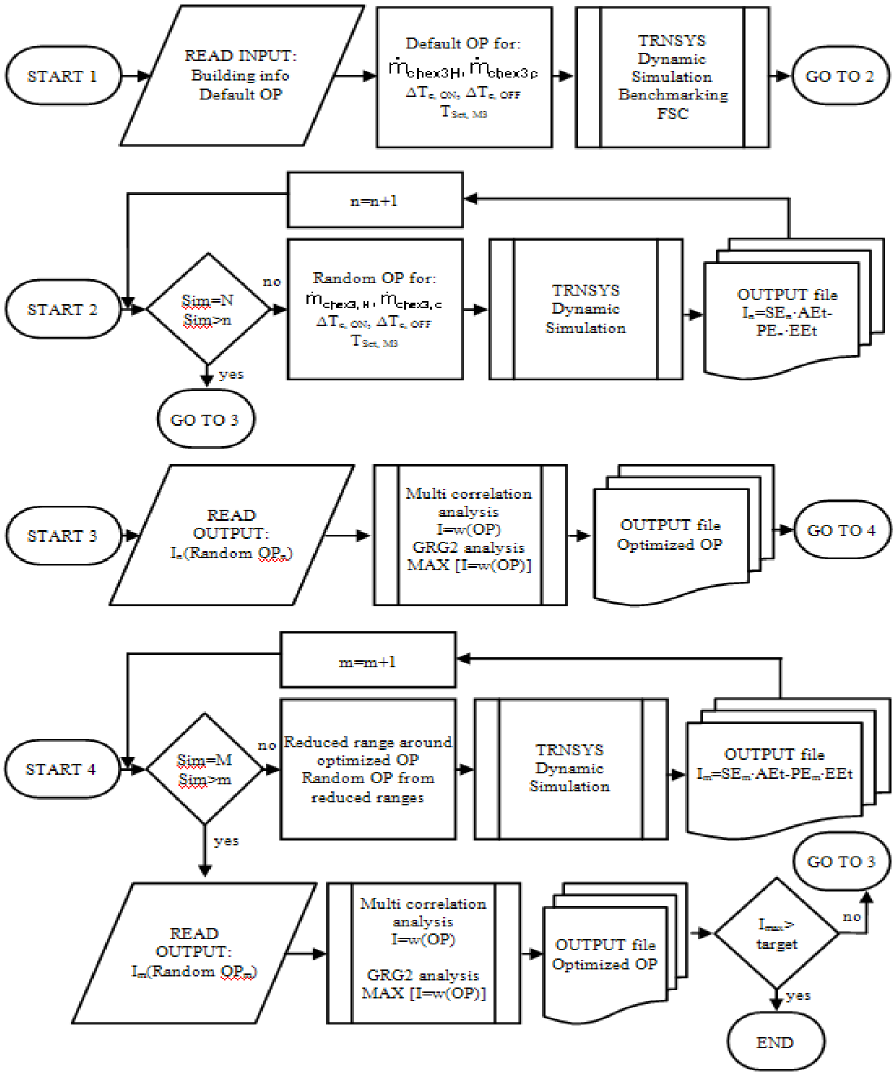

Fig. 2 Algorithm used for optimisation of the solar combisystem under exam.

For this study the fractional thermal energy savings ($f_{\mathrm{sav,therm}}$) and extended fractional energy savings ($f_{\mathrm{sav,ext}}$) have been used as benchmarks. The fractional energy savings represents the amount of primary energy saved by the combisystem compared with a reference system (Eq. (3)).

$$f_{sav,therm} = 1 - \frac{\dfrac{Q_{boiler}}{\eta_{boiler}}}{\dfrac{Q_{boiler,ref}}{\eta_{boiler,ref}}} = 1 - \frac{E_{aux}}{E_{ref}} \qquad (3)$$

Where Q_{boiler} represents the amount of energy produced by the auxiliary boiler, η_{boiler} is the efficiency of auxiliary boiler (assumed as 0, 8), $Q_{boiler,ref}$ is the amount of energy produced by the auxiliary boiler in reference system, $\eta_{boiler,\mathrm{ref}}$ is the efficiency of auxiliary boiler in reference system (assumed as 0, 8).

The extended fractional energy savings are taking into account also parasitic electrical energy consumption of the solar combisystem and a reference system (Eq. (4)).

More detailed explanation of $f_{sav,therm}$ and $f_{sav,ext}$ functions could be found in Ref. [5].

$$f_{sav,ext} = 1 - \frac{\dfrac{Q_{boiler}}{\eta_{boiler}} + \dfrac{W_{par}}{\eta_{el}}}{\dfrac{Q_{boiler,ref}}{\eta_{boiler,ref}} + \dfrac{W_{par,ref}}{\eta_{el}}} = 1 - \frac{E_{total}}{E_{total,ref}} \qquad (4)$$

Where W_{par} represents the parasitic electricity consumption, η_{el} is the efficiency of electricity production, $W_{par,\ \mathrm{ref}}$ is the parasitic electricity consumption of reference system.

As a reference system for this study the same system described in Fig. 1 was used, but without solar collectors and solar loops. This means that in the reference system energy consumption for SH, DHW and loss compensation from the tank are covered only by the auxiliary heater. Reference consumption of the primary energy for this system is calculated as shown in Eq. (5).

$$E_{ref,month} = \frac{(Q_{SH} + Q_{DHW} + Q_{loss,ref})}{\eta_{boiler,ref}} \qquad (5)$$

Where O_{SH} represents the monthly heat consumption for space heating, Q_{DHW} is the monthly heat consumption for hot water preparation and recirculation, $Q_{loss,\ \mathrm{ref}}$ is the monthly heat energy losses from the heat accumulation tank.

The amount of available solar radiation $G_{gl,A}$ is calculated on a monthly basis multiplying the solar collectors area A (m^2) by the total solar radiation on collector surface H ($\mathrm{MWh/m}^2$). The usable solar energy was calculated using Eq. (6).

$$Q_{solar,usable} = \sum_{1}^{12} \min\,(E_{ref,month}, A \cdot H) \qquad (6)$$

FSC is representing the maximum theoretical fractional energy savings that could be reached if the solar system has no heat losses. The FSC is calculated on a monthly and yearly basis (Eq. (7)).

$$\mathrm{FSC} = \frac{Q_{solar,usable}}{E_{ref}} \qquad (7)$$

Dynamic simulation using random sampling: The compact solar combisystem (Fig. 1) has been modeled in TRNSYS. The model has been tested and validated by Zandeckis [13]. Building information is input to the TRNSYS model using load profiles for SH and DHW, which are compiled as ASCII files. For space heating hourly data are used, while for DHW 10 min profile (or less) is used.

The optimization function includes five OP as variables. The simulation of the TRNSYS model using all possible multi-combination of these variables would take too much computation effort and time, even for relatively large steps applied to the ranges of the variables. Therefore a representative number of dynamic simulations are run with random selection of the five OP. For the generation of random OP has been used the standard Excel RANDBETWEEN function, which generates random numbers from uniform distributions between determined ranges.

The yearly results of each simulation (useful solar energy gains and parasitic electricity consumption) are saved in a dedicated output file.

Multi-correlation analysis: The outputs from the simulations, running random OP inputs, are statistically processed using the Marquardt's method. This method is used for implementing a non-liner regression analysis for the following polynomial function (Eq. (8)).

$$\begin{aligned} I = {} & a_1\dot{m}_{c,hex3,h} + a_2\dot{m}^2_{c,hex3,h} + a_3\dot{m}_{c,hex3,c} + a_4\dot{m}^2_{c,hex3,c} \\ & + a_5\Delta T_{c,ON} + a_6\Delta T^2_{c,ON} + a_7\Delta T_{c,OFF} + a_8\Delta T^2_{c,OFF} \\ & + a_9 T_{Set,M3} + a_{10} T^2_{Set,M3} \end{aligned} \qquad (8)$$

The Marquardt's method identifies the coefficient of the polynomial function ($a_1 \dots a_{10}$)with a numerical solution by a least squares curve fitting. For this analysis is used the computer tool StatGraphics. Next, the polynomial function is maximized using the GRG2 method. The GRG2 method is implemented in Excel environment using Solver. In this way an optimized set of OP is identified.

This set of OP can be further refined. The optimized set of OP can be expressed as a range of value, where the optimized OP is the mean value. Using these new refined ranges is possible to re-implement: the dynamic simulation using random sampling in the restricted range; the multi-correlation analysis and then the GRG2 analysis.

4. Case Study

The methodology proposed in this paper has been used for the optimisation of a compact solar and pellet combisystem installed in Sigulda, which is a city in Latvia with a population of about 11,000 inhabitants.

This solar combisystem was installed for a four storey multi-family building. In this specific case the system consisted of: a wood pellet boiler with a nominal capacity of 100 kW, solar collectors with total absorber area of 37.38 m^2, yearly space heating consumption (normalized) of 152 MWh, DHW consumption of 96 MWh.

Benchmarking analysis: The FSC for the demonstration project in Riga is calculated on a monthly and yearly basis. The monthly results of the calculations are presented in the Table 1. The total FSC for this system is 0.142, which represent the maximum upper benchmark value for this system.

Theoretically in this demonstration project all available solar radiation could be used (Fig. 3).

The lower benchmark scenario of the solar combisystem is simulated using the OP given by the manufacturers and installers (Table 2). This scenario represents the case which typically would occur without optimization. For this scenario the FSC are shown in Fig. 5.

With this operating parameters the income (*I)* for the solar combisystem are 755 US$.

Optimization: The proposed methodology described in paragraph 3 has been used for the identification of an optimized set of OP in this demonstration project.

As a first step 1000 dynamic simulations using random input of OP have been computed. Then using the Marquardt's method the coefficients of the polynomial function have been calculated. The R^2 statistic indicated that the model as fitted explains 68.07 % of the variability in the dependent variable *I*.

Using the GRG2 the polynomial equation was optimized providing a first set of optimized OP. The routine was implemented again. This time the random

Table 1 Results of calculations of FSC values, in MWh.

	Jan	Feb	Mar	Apr	May	Jun
$E_{ref,month}$	46.89	41.21	39.14	29.88	12.02	9.76
$G_{gl,A}$	1.59	2.61	4.25	4.88	6.10	6.21
$Q_{solar,usable}$	1.59	2.61	4.25	4.88	6.10	6.21
FSC	0.034	0.063	0.109	0.163	0.508	0.636
	Jul	Aug	Sep	Oct	Nov	Dec
$E_{ref,month}$	10.13	10.14	9.98	22.87	35.68	43.78
$G_{gl,A}$	6.17	5.30	3.82	2.37	0.39	0.61
$Q_{solar,usable}$	6.17	5.30	3.82	2.37	0.39	0.61
FSC	0.609	0.523	0.383	0.104	0.011	0.014

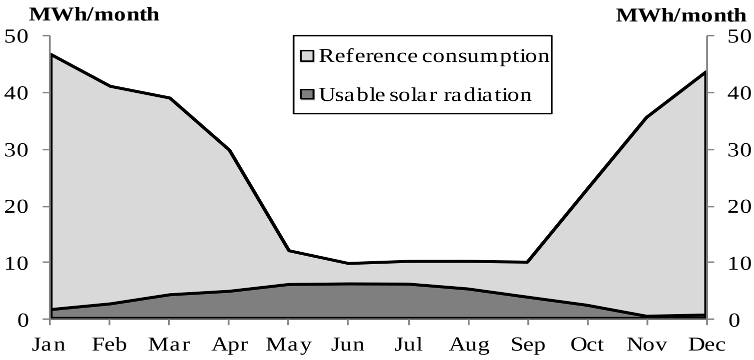

Fig. 3 Results of calculations of FSC values, in MWh.

Table 2 OP of the low benchmark scenario.

$IN_{c,hex3,h}$ kg/h	$IN_{c,hex3,h}$ kg/h	ΔT_{ON} ℃	ΔT_{OFF} ℃	$T_{set,M3}$ ℃
539	526	10	1	38

Table 3 Optimized set of OP.

$IN_{c,hex3,h}$ kg/h	$IN_{c,hex3,h}$ kg/h	ΔT_{ON} ℃	ΔT_{OFF} ℃	$T_{set,M3}$ ℃
371	380	14	6	45

Table 4 Optimised performances compared to benchmark.

	Q_{boiler}, MWh	W_{par}, MWh	Q_{solar}, MWh	ΔQ_{solar}, b%
Lower benchmark	233.84	0.176	15.091	-
Optimized scenario	232.13	0.240	16.728	+10.8

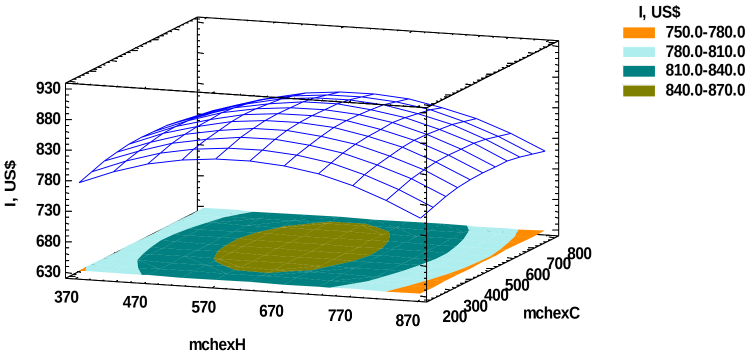

Fig. 4 Variation of *I* depending from the flow rates at the primary and secondary side of the solar heat exchanger.

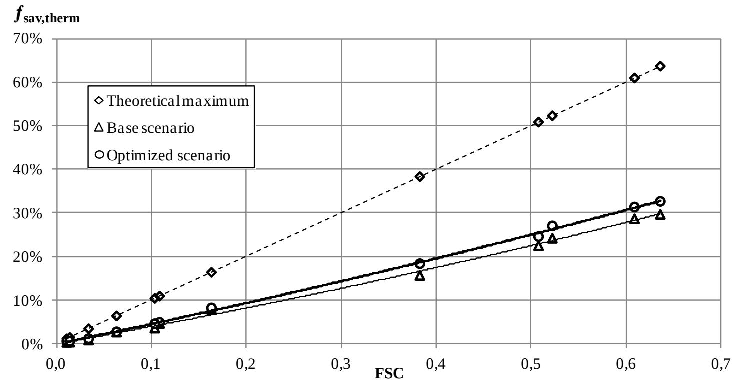

Fig. 5 Comparison of the optimized solar combisystem with the upper and lower benchmark values.

input of OP were selected from a restricted range of OP around the first optimized set of values. In this second case 100 dynamic simulations were implemented and the R^2 statistic of the refined polynomial function indicated that the model as fitted explains 98.60 % of the variability in the dependent variable I.

The optimized set of OP stated using the GRG2 on the refined polynomial equation are shown in Table 3.

The results of the analysis in comparison to the benchmark scenario are presented in the Table 4.

For the optimized system the solar energy gain have increased by 10.8 % or 1.637 MWh. The studied system is designed for low solar energy fractions, therefore improvements shoved only 0.69 % increase of $f_{\text{sav,therm}}$ and 0.64 % increase of in terms $f_{\text{sav,ext}}$.

As example in Fig. 4 are plotted the values of *I* in function of two OP, which are the flow rates at the primary and secondary side of the solar heat exchanger.

In energy terms the performance of the solar combisystem, in comparison to the upper and lower benchmark are shown in Fig. 5.

With the optimized set of OP the income I of the solar thermal system is 870 US$.

5. Conclusions

This methodology, with minimum computation effort, allows the identification of an optimized set of OP, which the plumber can program and regulate during the installation of the compact solar combisystem at a specific site.

The methodology has been applied to a case study, where the solar pellet combisystem is installed in a multifamily residential building in Latvia.

Compared to the lower benchmark value, which represent the performance of the non-optimized system, the income from the solar energy increases from 755 US$ to 870 US$. In energy terms the optimized system has 10.8% higher solar energy gains.

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